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## FREE MOLECULE HEAT TRANSFER IN THE IONOSPHERE

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GENERAL  ELECTRIC

# SPACE SCIENCES LABORATORY

THEORETICAL FLUID PHYSICS SECTION

## FREE MOLECULE HEAT TRANSFER IN THE IONOSPHERE

By

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R65SD41

January, 1965

MISSILE AND SPACE DIVISION

GENERAL  ELECTRIC

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## ABSTRACT

The potential energy stored in the ionosphere in terms of the atomic particles is substantial, and the energy released in the recombination processes taking place at the surface of the vehicle can therefore contribute substantially to the overall heat transfer.

In order to evaluate the importance of these chemical effects, the usual free molecular heat transfer and mass flux expressions are modified in this study to allow for a multi-component chemically reacting mixture of gases. These expressions include the effects which result from the recombination interactions at the solid-gas interface caused by the transport of atomic and ionized particles to the vehicle.

Results of the numerical solutions are presented graphically as functions of the altitude and flight velocity. The magnitudes of the various modes of energy transferred to the vehicle are compared. In particular, it is shown that for many free molecular situations of interest (i.e., flight speeds which are equal or greater in magnitude than escape velocities), the kinetic terms in the transfer equations are the dominant ones. However, for certain attainable combinations of altitude and flight speed and when all radiative heating is neglected, the total energy transfer can exceed the available kinetic energy by a factor as large as four.

*Auth. H*

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# SYMBOLS

A	Area
$c_K$	Mass fraction of species K
C	Velocity
$\epsilon$	Internal energy of diatomic particles
E	Energy flux, BTU/ft. <sup>2</sup> sec.
f	Distribution function
g	Acceleration of gravity, 32.2 ft./sec. <sup>2</sup>
$\Delta h_{fK}^o$	Heat of formation of species K, BTU/lb.
$I_K$	Ionization potential of species K, BTU/lb.
J	Mechanical equivalent of heat, 778 ft.lb./BTU
$h$	Boltzmann constant
$m_K$	Mass of species K, lb./Particle
$\dot{m}_K$	Mass flux of species K, lb./ft. <sup>2</sup> sec.
$M_K$	Molecular weight, lb./lb.-mole
$n_K$	Number flux of species K, Particles of species K/ft. <sup>2</sup> sec.
$N_K$	Number density of species K, Particles of species K/ft. <sup>3</sup>
$N_o$	Avogadro's number
$Q_w$	Net heat transfer to surface
$R_K = \frac{R}{M_K}$	Gas constant of species K, ft. lb./lb. °R
$R = k N_o$	Universal gas constant, 1.545 x 10 <sup>3</sup> ft.lb./lb.-mole °R
$S_K = \frac{V}{V_K}$	Molecular speed ratio of species K
T	Temperature, °R

## SYMBOLS (Cont'd)

$$\overline{V}_K = \sqrt{2gR_K T}$$

Most probable random speed of species K,  
ft./sec.

V

Mass flow velocity, ft./sec.

$$\text{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-x_1^2} dx_1$$

Error function, dimensionless

$\alpha$

Thermal accommodation coefficient,  
dimensionless

$\gamma$

Catalytic efficiency factor, dimensionless

$\epsilon$

Emissivity of surface, dimensionless

$\theta$

Angle between incident particles and surface

$\rho$

Density, lb./ft.<sup>3</sup>

$\sigma$

Stefan - Boltzmann constant for black body,  
 $4.761 \times 10^{-13}$  BTU/ft.<sup>2</sup>sec. (°R)<sup>4</sup>

$X_K$

Dimensionless quantity defined in equation 3

$\Psi_K$

Dimensionless quantity defined in equation 6

## SUBSCRIPTS

eq.

Equilibrium

K

Species K

Rad.

Radiation

S

Surface material

S. L.

Sea Level

w

Surface conditions, surface flux

x, y, z

Cartesian coordinate system

$\infty$

Free stream conditions, incident flux

$\phi$

Mode of energy

## INTRODUCTION

During the initial phase of entry into any planetary atmosphere, heat transfer to the surface of the vehicle occurs by means of direct collisions of the free stream particles with the vehicle. At these highest altitudes of any given entry trajectory (see Fig. 1), the gas density is very low and the mean free path of the gas particles is significantly larger than a typical vehicle dimension. In this non-continuum free molecular flight regime the response of the vehicle to the environmental interactions is measured in terms of energy and momentum accommodation coefficients. In other words, the heat transfer occurring at these altitudes is dependent upon the manner and degree to which the surface of the vehicle thermally accommodates the free stream impinging gas particles.

A parameter used as a criterion to determine whether or not free molecular flow conditions exist is the Knudsen number. The Knudsen number,  $Kn$ , is a dimensionless quantity expressing the ratio of the mean free path of the gas (see Fig. 2) to some significant characteristic dimension of the body. Knudsen numbers in excess of ten provide generally acceptable conditions for a free molecular flow environment. A complete theory for this type of energy transfer has been developed and is given in reference 1.



## FREE MOLECULAR ENERGY FLUXES

In order to determine the total energy transported to the body by the impinging free stream particles, it is first necessary to determine the number of particles of a particular type which strike the body. Since the medium in which the body moves is one of extreme rarefaction, relatively few intermolecular collisions will occur in the vicinity of the body, and the incident flow behaves effectively as if no object were present. This basic assumption of free molecular flow permits one to describe separately the fluxes of individual species in the gas in terms of maxwellian equilibrium distribution functions.

The number of particles of species K incident upon an elemental area per unit time may be written as:

$$n_K = N_K \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_0^{\infty} C_x f dC_x dC_y dC_z \quad (1)$$

where  $C_x$ ,  $C_y$ , and  $C_z$  are the components of the total absolute velocity  $C$ , which includes the macroscopic velocity of the gas as well as the thermal velocity of species K. The elemental surface area ( $dA$ ) is oriented such that  $dA \sin\theta$  is the projected cross-sectional area normal to the incident particles which flow in the positive  $x$  direction. The quantity "f" is the thermal distribution function (ref. 2) for the thermal velocities of the  $K^{\text{th}}$  species with a superimposed macroscopic gas velocity  $V_{\infty}$ .

Eq. (1) may be integrated to obtain the following expression for the free molecular number flux of particles of species K.

$$n_K = \frac{N_K \bar{V}_K X_K}{2\sqrt{\pi}} \quad (2)$$

where the dimensionless group  $X_K$  has the following dependence upon the molecular speed ratio and angular orientation.

$$X_K = e^{-(S_K \sin \theta)^2} + \sqrt{\pi} S_K \sin \theta \left[ 1 + \operatorname{erf}(S_K \sin \theta) \right] \quad (3)$$

The total flux of translational energy transported by the particles of the  $K^{\text{th}}$  species incident upon a unit surface area is expressed as:

$$\left(E_{\text{Trans.}\infty}\right)_K = \frac{m_K N_K}{2} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_0^{\infty} (C)^2 C_x f dC_x dC_y dC_z \quad (4)$$

which becomes, when integrated:

$$\left(E_{\text{Trans.}\infty}\right)_K = n_K \left( \frac{m_K V_{\infty}^2}{2} + \Psi_K \mathcal{A} T \right) \quad (5)$$

The two terms in Eq. (5) represent the contribution by species K to the total directed translational (kinetic) energy and the total random translational (thermal) energy. The dimensionless quantity  $\Psi_K$  which represents the portion of the internal energy of the particles due to random translational motion is given as:

$$\Psi_K = \frac{5X_K e (S_K \sin \theta)^2 - 1}{2X_K e (S_K \sin \theta)^2} \quad (6)$$

The total energy incident upon the elemental area of surface in a free molecular flow regime may therefore be written as:

$$E_{\infty} = \sum_K n_K \left[ \frac{m_K V_{\infty}^2}{2gJ} + \frac{\mathcal{A} T}{J} (\Psi_K + \mathcal{E}_K) + m_K (\Delta h_{f_K}^{\circ} + I_K) \right]_{\infty} \quad (7)$$

The three terms in the brackets are, respectively, the kinetic energy, the internal energy, and the chemical energy of the particles. The dimensionless quantity  $\mathcal{E}_K$  includes the rotational and vibrational energies carried by the diatomic particles. The chemical energy term includes the heat of formation of the neutral atomic species ( $\Delta h_{f_K}^{\circ}$ ) and the ionization potential ( $I_K$ ) of the charged species. (See Table 1).

An object in near space may also be heated as a result of radiation from several sources. This radiation includes direct solar radiation, direct radiation from the earth and the solar radiation which is scattered by the earth back into space, (albedo).

The surface energy flux,  $E_w$ , is defined to be the flux of energy directed away from the surface if the incident particles had been reflected diffusely. For diffuse reflection the gas would have no macroscopic velocity with respect to the surface and would be in maxwellian equilibrium at the surface temperature. The surface particles would have a microscopic velocity, however, which is associated with their random motion equilibrated to the thermal energy of the surface.

In accordance with the definition of ( $E_w$ ), the surface energy flux is written as follows:

$$E_w = \frac{\rho_w}{2\sqrt{\pi}} \left[ \frac{T}{J} \sum_K c_K R_K \bar{V}_K (\Psi_K + \epsilon_K) + \sum_K c_K V_K (\Delta h_{f_K}^o + I_K) \right]_w \quad (8)$$

Note that Eq. (8) includes the contributions of the internal and chemical energies of the particles. Note also that the effects of surface radiation are treated separately.

In order to ascertain the magnitude of the chemical energy terms in Eq. (7) and (8) which depends upon the relative densities of the atomic and ionized particles, a knowledge of the chemical composition of the ionosphere is required.

## POTENTIAL CHEMICAL ENERGY OF THE IONOSPHERE

The structure of the upper atmosphere, in terms of the concentration of species, depends upon interactions among several types of processes. These processes are known as: mixing of the species; diffusive equilibrium; photochemical dissociation and radiochemical ionization. Since the concentrations of the atomic and ionized species at high altitudes depend, to a great extent, upon the amount and nature of the solar radiation incident upon the upper atmosphere, the relative densities of these species may be expected to vary with time of day, season of the year, latitude with respect to the earth's surface, and solar activity. Furthermore, it should be noted that estimates of the chemical composition of the upper atmosphere are continually undergoing revision as a result of the high altitude rocket data and satellite measurements which have been made in the past few years, and therefore, any heat transfer calculations using data presently available will provide only reasonable estimates.

The composition models of references 3 and 4 are presented in figures 3 and 4, and thereby indicate the variation of the concentrations of the dominant chemical species with altitude up to 500,000 ft. For this altitude range the concentrations of electrons and ionized species are found to be negligible with respect to the overall energy transfer process.

Using the data of figures 3 and 4, table 1, and the equation  $E_{(\text{chem.})_\infty} = (\sum_k C_k \Delta h_{f_k}^0)_\infty$  the maximum chemical energy available in the ionosphere for transfer to a fully catalytic surface may be calculated. The magnitude of the chemical energy potential using the composition model of ref. 3 is found to increase with altitude having a magnitude of approximately 1500 BTU/lb. at an altitude of 500,000 ft.

The chemical energy density, defined as the product  $\rho_\infty E_{(\text{chem.})_\infty}$ , has an interesting behavior in this altitude range. Since the free stream density ( $\rho_\infty$ ) is a decreasing function of altitude and, as mentioned above, the chemical potential increases with altitude, the ambient chemical energy density is found to have a maximum at an altitude of approximately 325,000 ft. (see Fig. 5). However, an order of magnitude difference is noted between the two chemical composition models.

In order to determine the portions of the incident energies (i. e. kinetic, internal or chemical) which are transferred to the surface, detailed information is needed concerning the interactions of the impinging particles with the solid.

## SURFACE INTERACTION PARAMETERS

In general, the reflected particles will not have their energies completely accommodated to the surface conditions after a single collision. They will probably rebound at some energy intermediate between the surface conditions and ambient conditions. The usual procedure is to define average parameters which characterize the interaction phenomena.

The thermal accommodation coefficient  $\alpha$  is the parameter used to specify the degree to which a particular form of energy, not including chemical,  $E'_{K, \phi}$  carried by one type of incident particle (species K) is accommodated by a surface composed of material "S".

$$\alpha_{K, \phi, S} = \left( \frac{E'_{\infty} - E'_R}{E'_{\infty} - E'_W} \right)_{K, \phi, S} \quad (9)$$

$E'_R$  is the energy which is actually transported away from the surface by the reflected particles.

The numerical limits for the thermal accommodation coefficients (as defined by equation 9) are seen to be zero, corresponding to the case of specular reflections, and unity for diffuse reflections. Values of the thermal accommodation coefficients have been measured (see table 2) for static gases in contact with different types of surfaces. The applicability of data of this nature to the possible gas-surface interactions likely to be encountered in high altitude hypersonic flight is highly uncertain.

The portion of the incident chemical energy which may be released at a surface depends upon the ability of the surface to promote catalytic atom recombination. If the surface has catalytic properties with respect to the impinging monatomic species, a certain portion of these atoms may be expected to recombine during the adsorption process and be re-emitted as diatomic particles. On the other hand, the diatomic particles in the free stream which also collide with the surface may dissociate upon being adsorbed and later desorb as atoms.

As an illustration, consider the following heterogeneous chemical reaction:



which for the catalytic recombination of oxygen atoms on a surface is actually a three body collision process where the surface particle B absorbs the heat of recombination.

In order to relate the incident and surface fluxes of the atoms and molecules, we utilize the definition of the gross catalytic efficiency factor  $\gamma$ .

$$\gamma = \frac{\text{collisions effective in causing recombination or dissociation}}{\text{total collisions}} \quad (11)$$

The following relationships can be shown to exist between the incident and re-emitted surface fluxes of atomic and molecular oxygen.

$$\dot{m}_{O_2_w} = \dot{m}_{O_2_\infty} + \gamma_O \left[ \dot{m}_{O_\infty} - \dot{m}_{O_2_\infty} \left( \frac{\dot{m}_O}{\dot{m}_{O_2}} \right)_{eq.} \right]_w \quad (12)$$

$$\dot{m}_{O_w} = \dot{m}_{O_\infty} - \gamma_O \left[ \dot{m}_{O_\infty} - \dot{m}_{O_2_\infty} \left( \frac{\dot{m}_O}{\dot{m}_{O_2}} \right)_{eq.} \right]_w \quad (13)$$

The free molecular mass flux of species K is given as:

$$\dot{m}_K = m_K n_K = \frac{\rho_K \bar{V}_K X_K}{2\sqrt{\pi}} \quad (14)$$

Note that the second term in the brackets of Eqs. (12) and (13) accounts for the fraction of the molecular particles which may dissociate on the surface prior to re-emission. Similar relationships may be written for the interactions of the nitrogen atoms and molecules. If the resulting equations are added and summed over all species (K), we obtain the steady state condition for the conservation of the mass flux upon reflection.

$$\left( \sum_k \dot{m}_K \right)_w = \left( \sum_K \dot{m}_K \right)_\infty \quad (15)$$

Existing data on the catalytic efficiency factors are quite meager. Some experimental values of the recombination coefficients for oxygen atoms on various surfaces are given in table 3.

In general, the net energy transferred to a surface in hypersonic flight in the free molecular regime, is the sum of the difference between the incident and reflected energy fluxes  $E'_\infty$  and  $E'_R$ , (including random and directed translational energy, rotational energy and vibrational energy), the portion of the potential chemical energy which is released during surface recombination, and the net radiant flux. A formal representation of the free molecular heat transfer, in terms of the surface interaction parameters and the energy fluxes previously discussed, is as follows:

$$Q_w = \sum_k \sum_\phi \alpha_{\phi, K, S} \left( E'_{K, \phi_\infty} - E'_{K, \phi_w} \right) + Q_{\text{chem.}_w} + Q_{\text{Rad.}_w} \quad (16)$$

Note that the summation over  $\phi$  includes the directed translational and internal modes of energy transfer. The heat transfer due to the heterogeneous chemical reactions is:

$$Q_{\text{chem.}_w} = \left[ \sum_K \dot{m}_K \Delta h_{fK}^0 \right]_\infty - \left[ \sum_K \dot{m}_K \Delta h_{fK}^0 \right]_w \quad (17)$$

The relationships between the incident and re-emitted mass fluxes ( $\dot{m}_K$ ) have the functional dependence upon the catalytic efficiency factors ( $\gamma_K$ ) as seen in Eqs. (12) and (13).  $Q_{\text{Rad.}_w}$  is the net radiant energy and may be written:

$$Q_{\text{Rad.}_w} = Q_{\text{Rad.}_\infty} - \sigma \epsilon_w T_w^4 \quad (18)$$

where the contributions to  $Q_{\text{Rad.}_\infty}$  have been discussed in the preceding section. It is noted, in passing, that the absorptivity of the surface of the space vehicle for all of the radiant energy of solar origin is higher than the low temperature surface emissivity ( $\epsilon_w$ ) for most metals and lower for many non-metals.



## DISCUSSION OF RESULTS

The kinetic energy portion of the heat conducted to the surface at the stagnation point for complete thermal accommodation is shown in Fig. 6. The free stream density values used in this calculation were obtained from references 5 and 6. Included in the figure, for comparative purposes, are the magnitudes of the radiative energy fluxes incident to the vehicle surface. For the hypersonic flight speeds shown here, the heat transfer as a function of the angle of attack will vary as  $\sin \theta$ . An exception to this heat transfer variation in  $\theta$  will occur for small values of  $\theta$ . It was found that the stagnation point heat transfer in free molecular flow exceeds the heat transferred to any portion of the body parallel to the flow by a factor approximately equal to the quantity  $2\sqrt{\pi} \bar{S}_\infty$ , where  $\bar{S}_\infty$  is defined to be the mean molecular speed ratio of the incident gas mixture. A correlation equation which approximates the variation in the kinetic energy transferred to the surface with the angle of attack was found to be:

$$Q_{W_{\text{kinetic}}} = \left[ Q_{W_{\text{(kinetic, stag.)}}} \right] \cdot \left[ \sin \theta + \frac{1}{2\sqrt{\pi} \bar{S}_\infty} \right] \quad (19)$$

The ratio of total to kinetic free molecular energy transfer is shown in figure 7 for flight speeds greater than 10,000 ft./sec. and in figure 8 for flight speeds less than 10,000 ft./sec. Both chemical models (i.e. refs. 3 and 4) are included for comparison. The assumptions made for these calculations were that of complete thermal accommodation, a fully catalytic surface, and a low surface temperature. Note also that the radiative energy transfer is excluded. The effect of utilizing thermal accommodation coefficients other than unity has the effect of shifting the general level of all the curves.

As might be expected, the figures show that for a given free stream dissociation level (altitude), the transport of chemical energy becomes less important and the kinetic energy term becomes increasingly dominate as the flight speed increases. It is apparent (figure 7) that for combinations of

altitudes less than 500,000 ft. and flight speeds greater than superorbital velocities the total energy transfer exceeds the available kinetic energy by less than ten percent. However, for the lower flight speeds at these high altitudes (see Figure 8), the total energy transfer exceeds the available kinetic energy by a factor as large as four. It is noted that these same combinations of altitude and flight speed (figure 8) encompass the trajectories of the present day experimental rocket planes, (see Figure 1).

The magnitude of the ratio  $Q_{\text{total}}/Q_{\text{kinetic}}$  for a given altitude, flight speed and surface material depends, in general, upon the relative values of the surface interaction parameters and the surface temperature. Let us expand this ratio and consider separately the variation of the internal energy term and the chemical energy term with surface temperature and the heterogeneous reaction parameters.

$$\frac{Q_{\text{total}}}{Q_{\text{kinetic}}} = 1 + \frac{Q_{\text{internal}}}{Q_{\text{kinetic}}} + \frac{Q_{\text{chemical}}}{Q_{\text{kinetic}}} \quad (20)$$

The contribution of the internal energy which is very small in comparison with the kinetic and chemical contributions, is primarily dependent upon the surface temperature. The maximum contribution this term makes to the overall heat transfer occurs when the surface temperature is lower than that of the free stream. As the surface temperature increases, the internal energy of the gas particles at the surface increases. When the wall temperature exceeds the temperature of the ambient flow, the transfer of internal energy away from the surface exceeds the incident internal energy and the overall heat transfer is decreased accordingly. Since it is currently felt that the translational and rotational energies are accommodated by a surface to approximately the same degree, the ratio  $Q_{\text{internal}}/Q_{\text{kinetic}}$  might be expected to be relatively insensitive to the values of the thermal accommodation coefficients.

The ratio of the chemical energy transfer to the kinetic energy transfer will have the same variation, in general, as the ratio of the catalytic efficiency factor to the thermal accommodation coefficient.

$$Q_{\text{chemical}}/Q_{\text{kinetic}} \sim \gamma/\alpha \quad (21)$$

Both  $\gamma$  and  $\alpha$  are known to vary with increasing surface temperature, but at different rates. Since the "chemical time" necessary for atom recombination is known to be appreciably longer than the "translational accommodation time", the ratio of  $\gamma$  to  $\alpha$  for reasonable surface temperatures may be expected to be less than unity.

For extremely high surface temperatures the chemical reactions occurring at the gas-solid interface will be those of dissociation. These endothermic reactions, in which the newly formed atoms absorb the heat of the reaction, considerably reduce the chemical energy transferred to the solid material.

## CONCLUSIONS

The uncertainties in any heat transfer calculation in the free molecular flow regime are at least threefold.

1. The fraction of the thermal energy (kinetic and internal) accommodated by the surface for hypersonic flow conditions is not known, because little data exists on  $\alpha_{K, \phi, S}$ .

2. The level of uncertainty in the composition of the upper atmosphere will produce significant changes in any heat transfer predictions especially for combinations of low hypersonic speed and high altitude environmental conditions.

3. The mechanism of surface catalysis is not as yet understood to the extent of adequately predicting the recombination coefficients for atoms in a hypersonic environment for different surface materials.

It is clear that although general relationships have been presented in this paper, a more precise determination of free molecular heat transfer in the ionosphere will depend on the availability of more experimental data.

TABLE 1  
HEATS OF FORMATION AND IONIZATION POTENTIALS

<u>CHEMICAL REACTION</u>	<u>ENERGY</u>
$O_2 \rightleftharpoons 2O$	$\Delta h_{fO}^o = 6,655 \text{ BTU/lb.}$
$N_2 \rightleftharpoons 2N$	$\Delta h_{fN}^o = 14,527 \text{ BTU/lb.}$
$NO \rightleftharpoons NO^+ + e^-$	$I_{NO^+} = 12,810 \text{ BTU/lb.}$
$O_2 \rightleftharpoons O_2^+ + e^-$	$I_{O_2^+} = 15,630 \text{ BTU/lb.}$
$O \rightleftharpoons O^+ + e^-$	$I_{O^+} = 35,310 \text{ BTU/lb.}$
$N \rightleftharpoons N^+ + e^-$	$I_{N^+} = 43,100 \text{ BTU/lb.}$

REF: Logan, J. G., "The Calculation of Thermodynamic Properties of Air at High Temperatures", Cornell Aeronautical Laboratory Report No. AD - 1052 - A - 2, June 1956.

TABLE 2  
THERMAL ACCOMMODATION COEFFICIENTS  $\alpha$

<u>Gas</u>	<u>Surface</u>	<u><math>\alpha</math></u>	<u>References</u>
O <sub>2</sub>	Bright Pt.	.81	7
O <sub>2</sub>	Black Pt.	.93	7
N <sub>2</sub>	Platinum	.50	8
N <sub>2</sub>	Tungsten	.35	8
Air	Bronze	.88 - .94	9
Air	Iron	.87 - .96	9
Air	Aluminum	.87 - .97	9
N <sub>2</sub>	Tungsten	.50 - .61	10

TABLE 3  
RECOMBINATION COEFFICIENTS FOR OXYGEN ATOMS  
(AT ROOM TEMPERATURE)

<u>Surface</u>	<u><math>\gamma</math></u>	<u>Reference</u>
Silver	$1.0 \times 10^{-2}$	11
Pyrex	$1.2 \times 10^{-4}$	12
Iron	$3.6 \times 10^{-2}$	13
Copper	$1.7 \times 10^{-1}$	13
Silver	$2.4 \times 10^{-1}$	13
Potassium Chloride	$5.0 \times 10^{-5}$	14
Lead Monoxide	$5.0 \times 10^{-2}$	14

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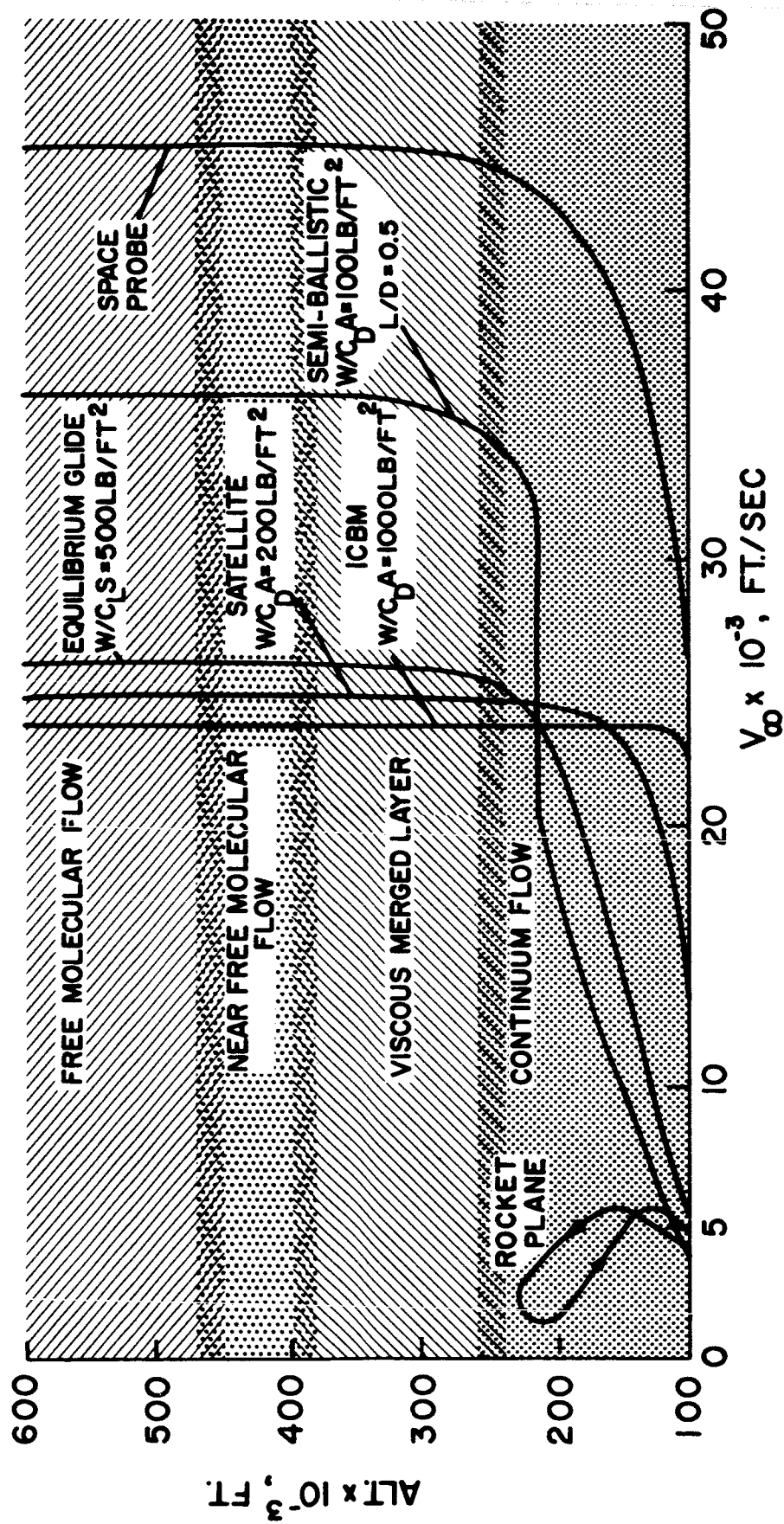


Figure 1. High Altitude Hypersonic Flight Regimes

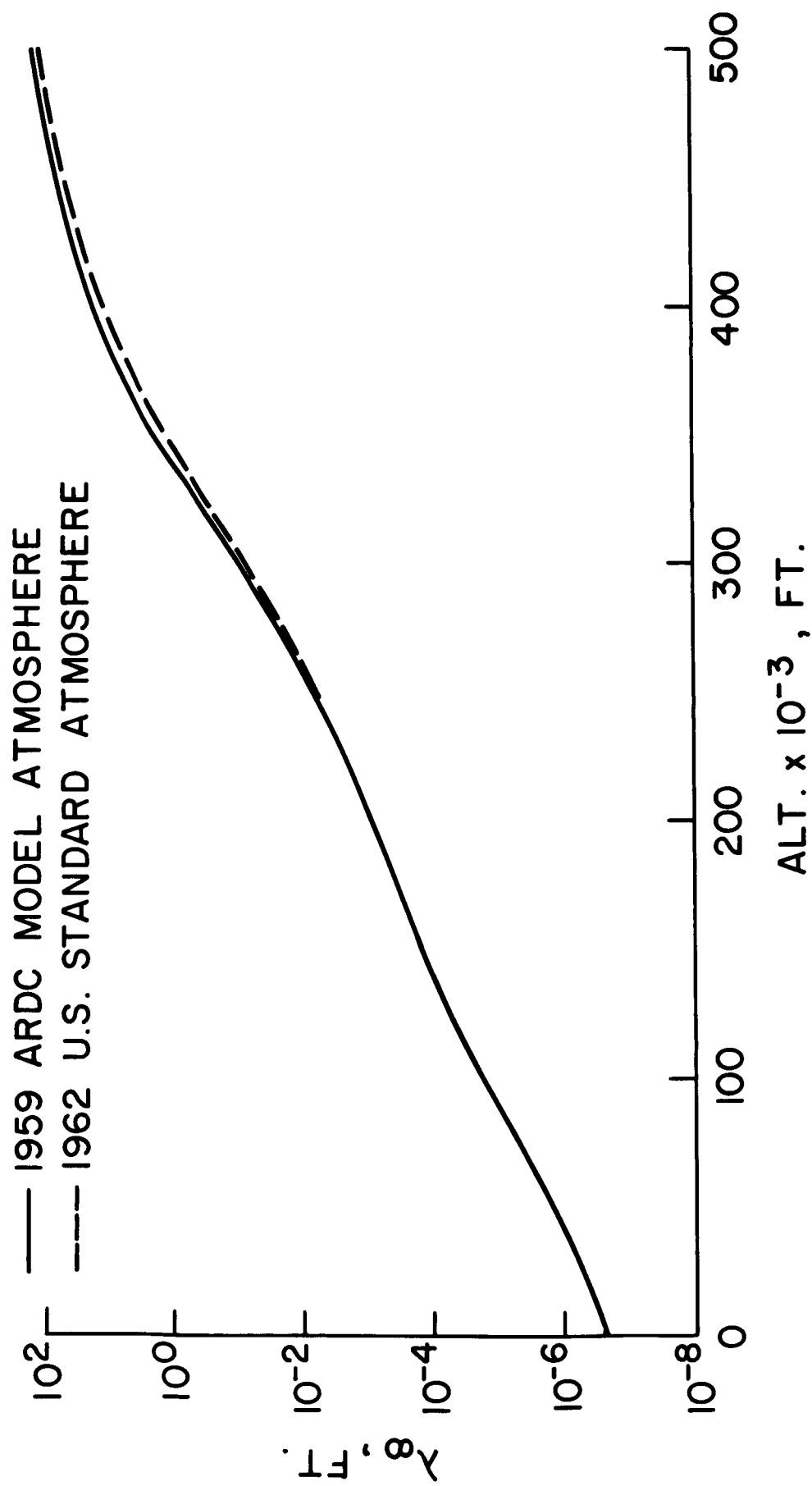


Figure 2. Variation of the Ambient Mean Free Path With Altitude

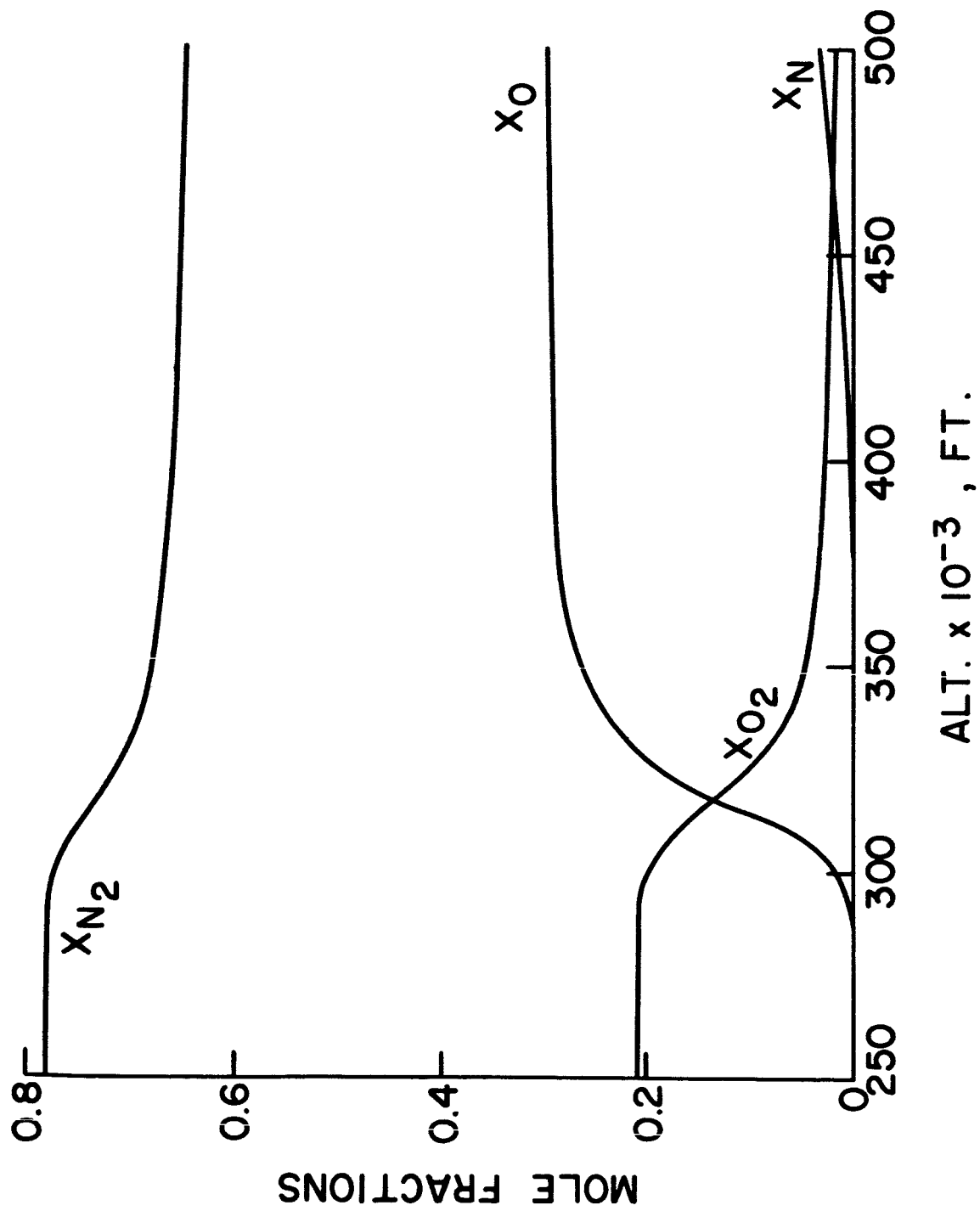


Figure 3. Atmospheric Composition at Extreme Altitudes, (Miller)

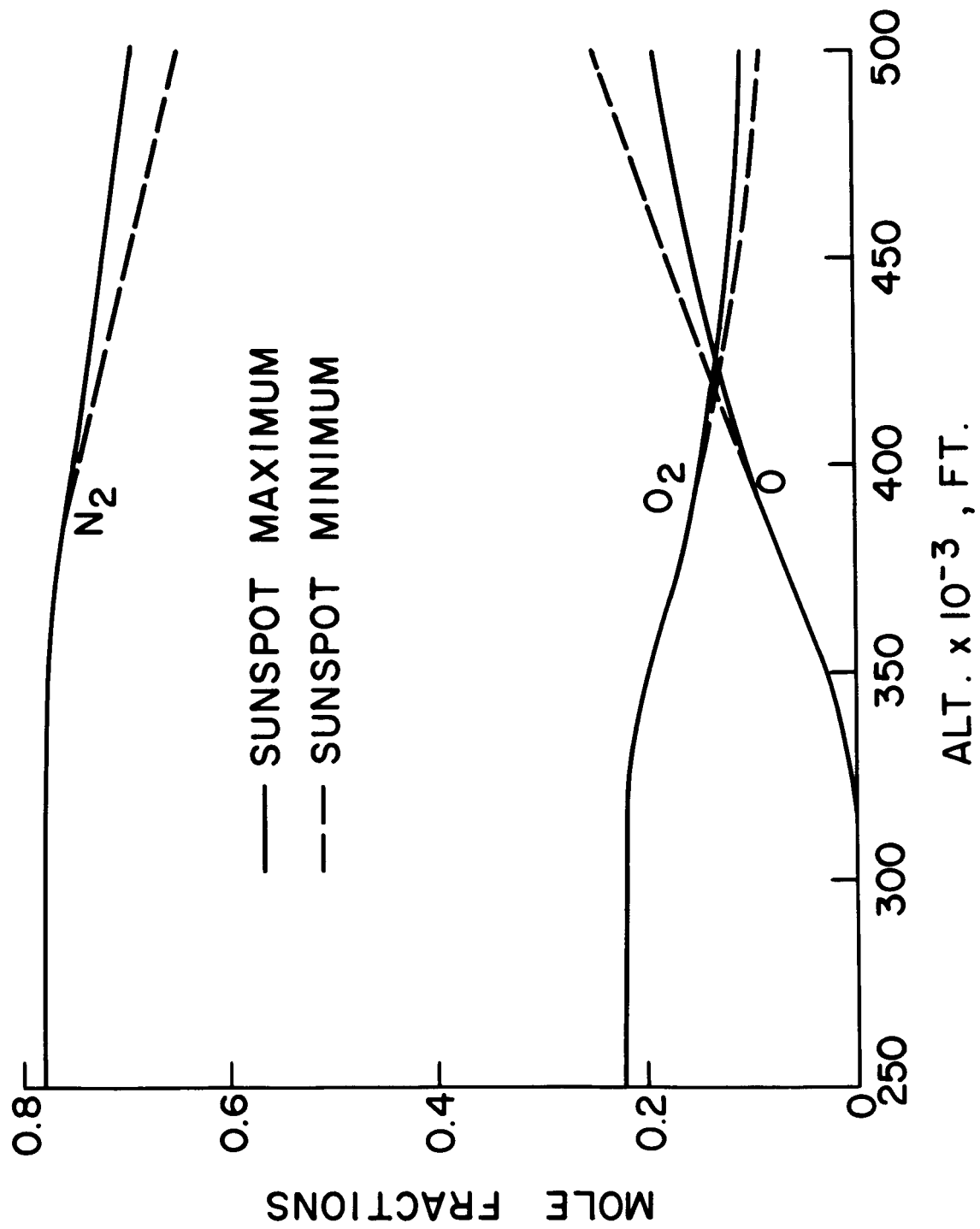


Figure 4. Atmospheric Composition at Extreme Altitudes, (Harris and Priestner)

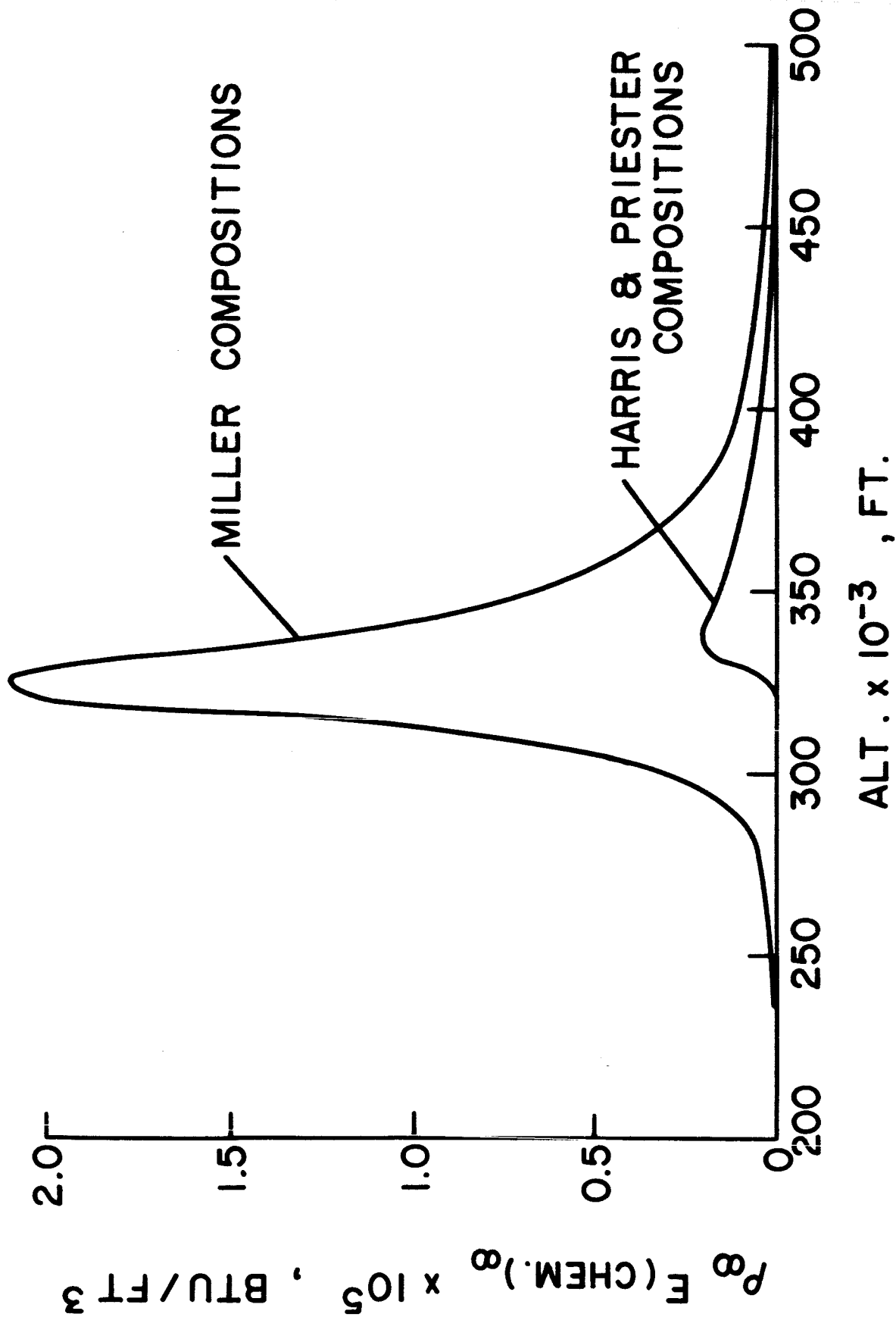


Figure 5. Ambient Chemical Energy Density

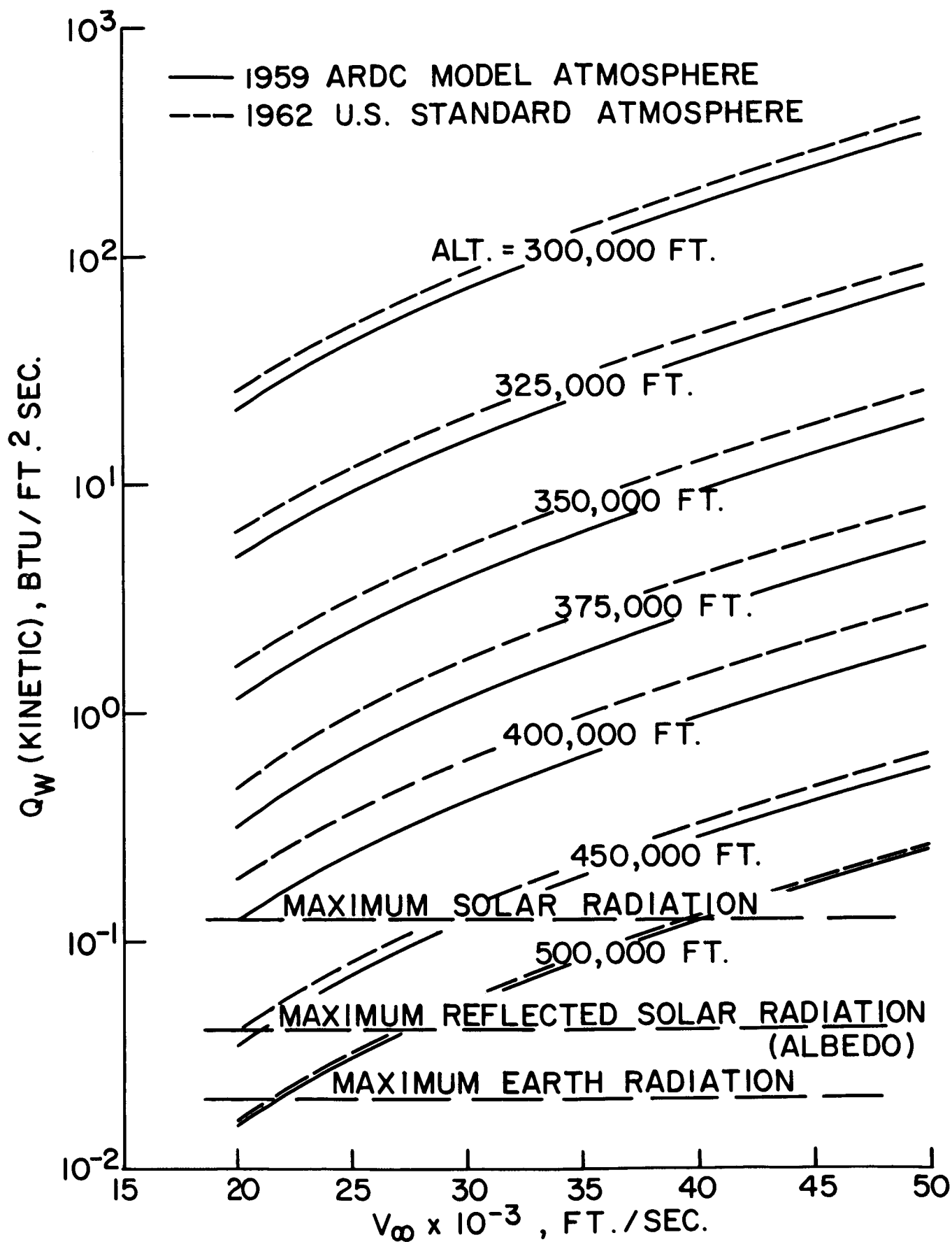


Figure 6. Kinetic Energy Transfer, Complete Thermal Accommodation, Free Molecular Flow at Stagnation Point

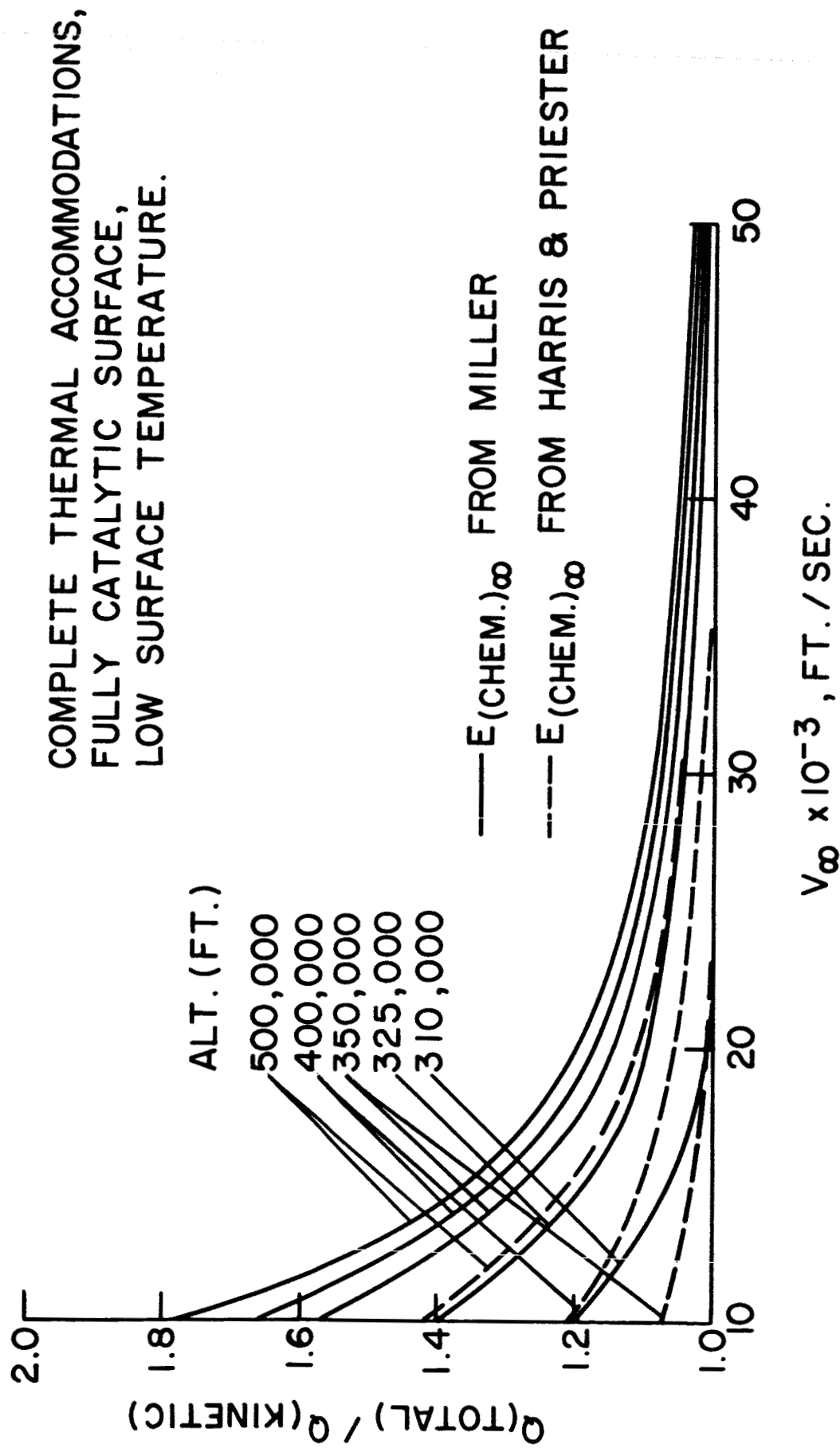


Figure 7. Free Molecular Energy Transfer, Excluding Radiation,  $V_{\infty} > 10,000 \text{ ft. / sec.}$



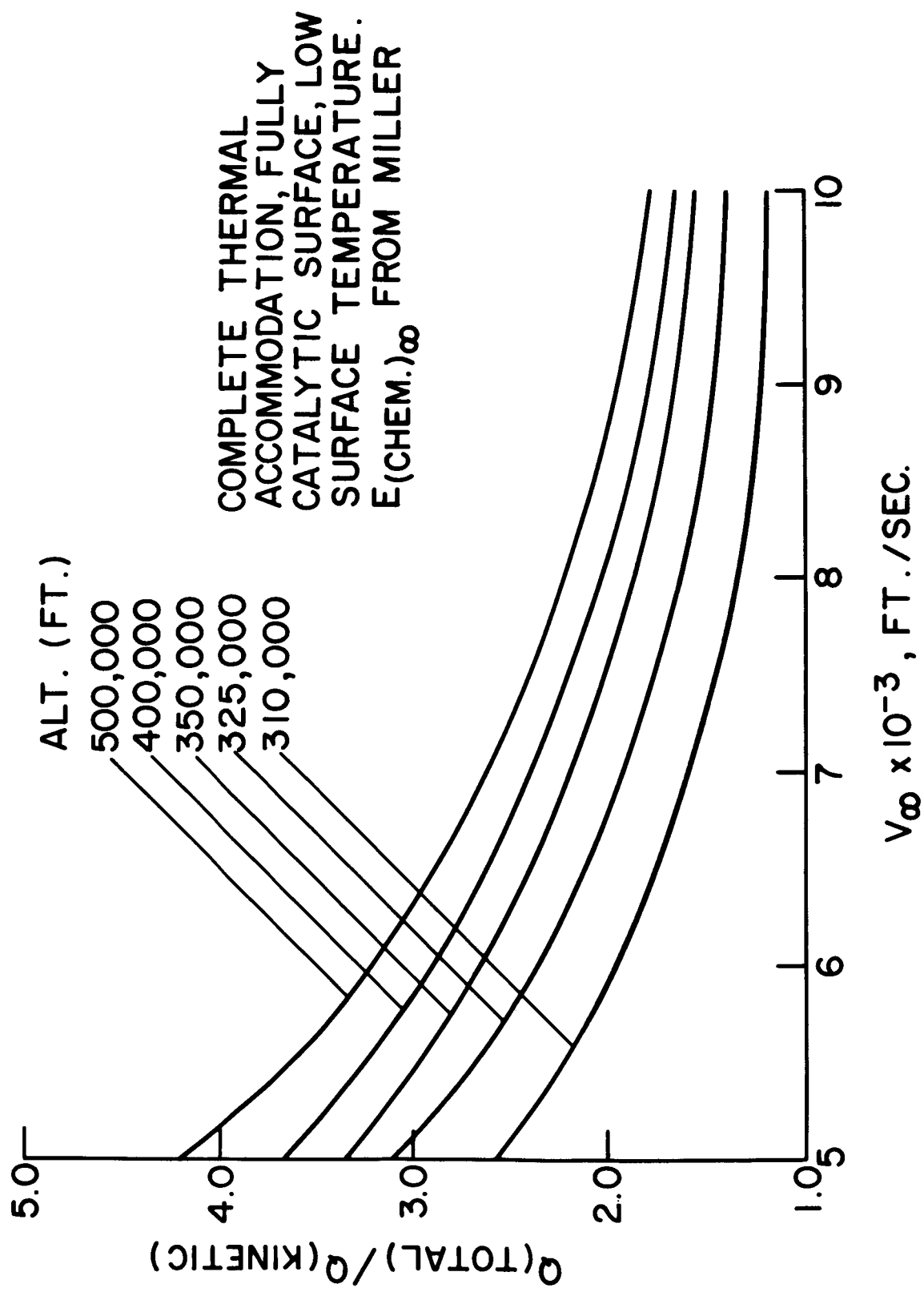


Figure 8. Free Molecular Energy Transfer, Excluding Radiation,  $V_{\infty} < 10,000$  ft./sec.

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TECHNICAL INFORMATION SERIES

AUTHOR L. M. Gilbert S. M. Scala	SUBJECT CLASSIFICATION Aerothermophysics	NO. R65SD41 DATE January, 1965
TITLE FREE MOLECULE HEAT TRANSFER IN THE IONOSPHERE		G. E. CLASS I GOV. CLASS U
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<p>SUMMARY Results of the numerical solutions are presented graphically as functions of the altitude and flight velocity. The magnitudes of the various modes of energy transferred to the vehicle are compared. In particular, it is shown that for many free molecular situations of interest (i. e., flight speeds which are equal or greater in magnitude than escape velocities), the kinetic terms in the transfer equations are the dominant ones. However, for certain attainable combinations of altitude and flight speed and when all radiative heating is neglected, the total energy transfer can exceed the available kinetic energy by a factor as large as four.</p> <p style="text-align: center;">14 UT1102</p>		
KEY WORDS heat transfer, molecules, collisions, kinetic energy		

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Theoretical Fluid Physics